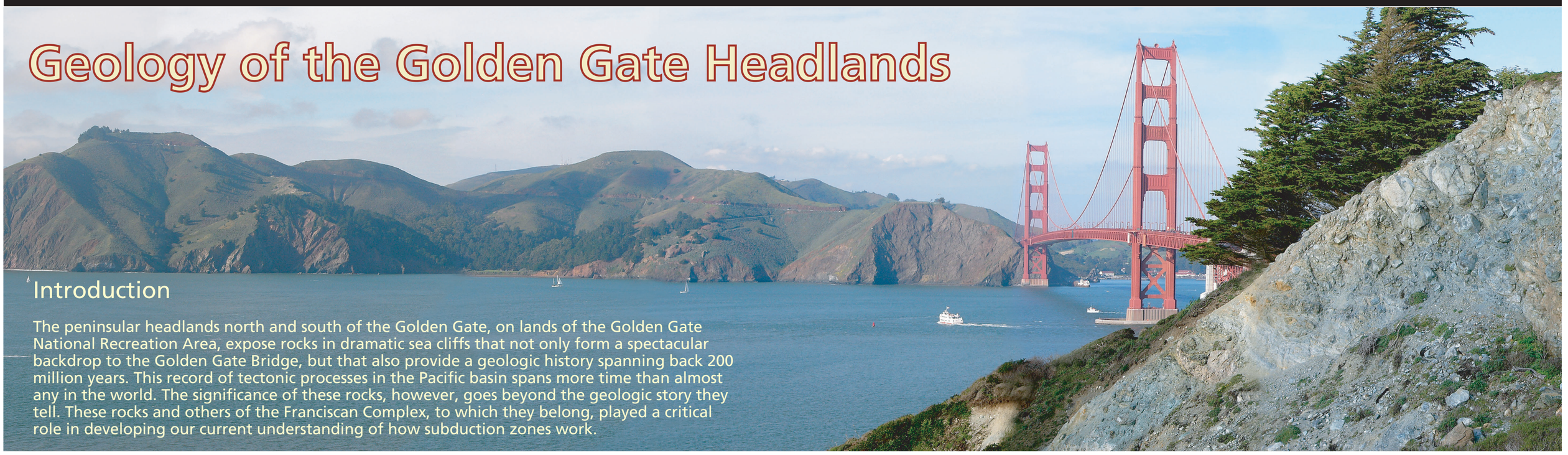
Geology of the Golden Gate Headlands

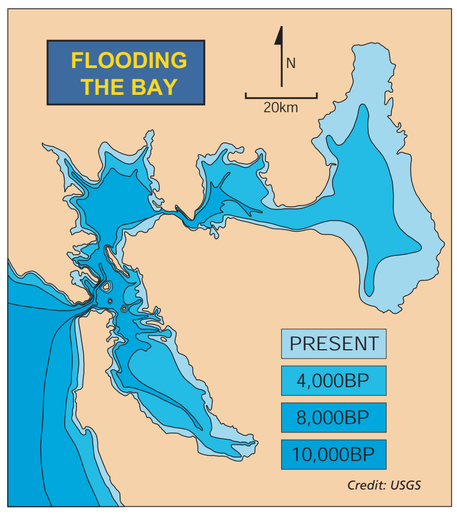


Introduction

The peninsular headlands north and south of the Golden Gate, on lands of the Golden Gate National Recreation Area, expose rocks in dramatic sea cliffs that not only form a spectacular backdrop to the Golden Gate Bridge, but that also provide a geologic history spanning back 200 million years. This record of tectonic processes in the Pacific basin spans more time than almost any in the world. The significance of these rocks, however, goes beyond the geologic story they tell. These rocks and others of the Franciscan Complex, to which they belong, played a critical role in developing our current understanding of how subduction zones work.

The Pacific Margin Today

San Francisco and the Golden Gate headlands are located on the boundary between two of the earth's great tectonic plates, the North American and Pacific plates. Today, this plate boundary is a *transform fault* (the plates are sliding past each other) and is formed by what is perhaps the best-known geologic feature of California, the San Andreas fault zone. Movement, totaling about 1 inch (2.5 cm) a year, along the San Andreas and its subsidiary faults, the Hayward and Calaveras, is infamous for producing the large earthquakes that rock California and also results in the area's beautifully rugged terrain. Major earthquakes occur several times each century on these and less well-known faults in the San Francisco area, releasing strain along the creeping plates.



After the last glacial maximum at 18,000 years ago, sealevel rose rapidly moving the shoreline eastward from west of the Farallones and entering the Golden Gate about 10,000 years ago.

The Franciscan Complex

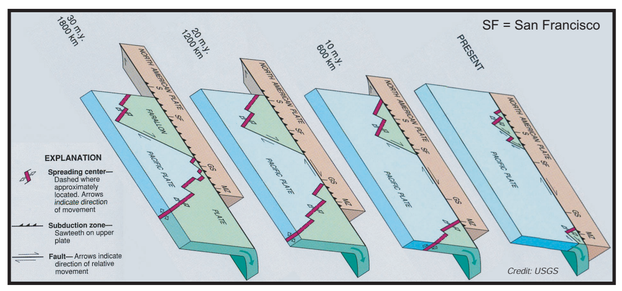
The San Andreas fault system is a relatively new geologic feature in the Bay Area; originating to the south 28 million years ago, and extending through the Bay Area only 6-10 million years ago. In contrast, older rocks of coastal California indicate that Pacific ocean floor was *subducted* (moved) beneath the western edge of the North American Plate before the San Andreas fault formed. The distinctive rocks of the world-famous Franciscan Complex, named at San Francisco and underlying much of coastal Northern California, formed in this subduction zone. Locally, Franciscan rocks range from about 200 million to 80 million years old.

Rocks of the Franciscan are highly fractured and disrupted and may be complexly mixed together to create what is called a *mélange* (French for "mixture" or "blend"). These disrupted rocks represent an *accretionary wedge*; a body of rock that accumulates in a subduction zone. Large areas of the Franciscan Complex are composed of blocks of rock miles across, called *terranes*. Every so often, these blocks were scraped off of the subducting oceanic plate, thrust eastward, and shingled against the western margin of North America. This process formed a stack of rocks in which the uppermost (on the east) are the oldest, and in which each major thrust wedge to the west becomes younger. Within each of the terrane blocks, however, the rocks become younger upwards, as is normal, but the rock sequence may be repeated many times by internal thrust faults.

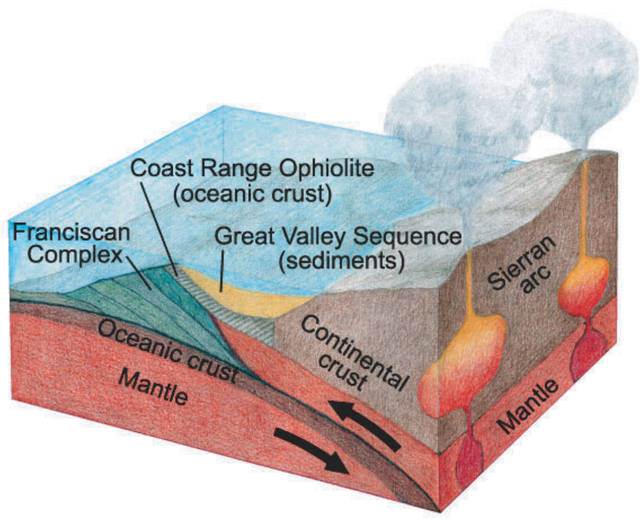
Major geologic features of the Bay Area.

Making San Francisco Bay

The valley in which San Francisco Bay resides began to form 2 to 3 million years ago, when the surrounding mountains and hills started to rise on either side. The first known *estuarine rocks* (marine influenced) were laid down only about 600,000 years ago. Rocks under the bay indicate up to seven different estuarine periods over the last half million years, developed during times of high sea level between glacial periods. During glacial periods, when vast quantities of ocean water were stored in continental glaciers, the bay floor became a valley and experienced erosion and down-cutting. At those times, the glacial-fed ancestral Sacramento River flowed through the bay valley and out the Golden Gate Straits. Ocean water started flooding today's San Francisco Bay about 10,000 years ago.



History of the San Andreas fault system.

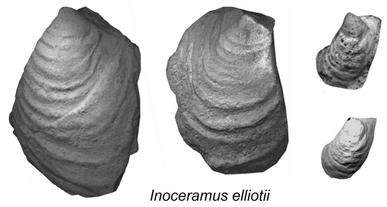


Block diagram showing subduction zone developed along the California coast during formation of the Franciscan Complex.

Franciscan Terranes of the Bay Area

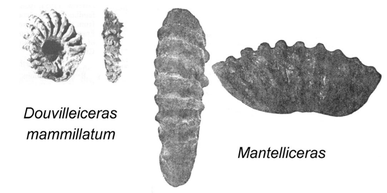
Franciscan terranes are composed of *oceanic rocks* that may include igneous basement material and overlying marine sedimentary rocks. Zones of mélange separate the terranes. In the Bay area, the Franciscan Complex is divided into eight terranes. This division is based on differences in rock types and ages, and in the degree to which their minerals have been altered by heat and pressure (metamorphic grade).

San Francisco and the Marin Headlands contain three terranes, from oldest to youngest, the Alcatraz, Marin Headlands, and San Bruno Mountain terranes. Separating the terranes are the Hunters Point and City College mélange zones, which are composed of broken serpentinite and shale with scattered pieces of basalt, chert, sandstone, and high-grade metamorphic rocks. The Alcatraz Terrane is mostly sandstone deposited by submarine landslides and contains fossil mollusks that lived 130 and 140 million years ago (Early Cretaceous). The Marin Headlands Terrane contains oceanic rocks including basaltic ocean crust, open-ocean chert deposits, and continental-derived sandstone. Fossils in these units indicate the chert was deposited from about 200 million to 100 million years ago (Early Jurassic to Late Cretaceous) and the sandstone between 100 and 90 million years ago. The San Bruno Mountain Terrane is mostly composed of sandstone and has yielded no fossils but is thought to be Late Cretaceous in age.



Inoceramus elliotii

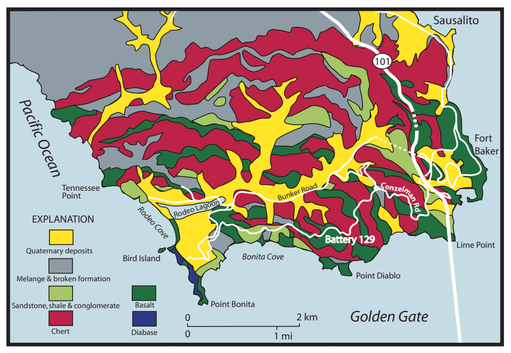
Molluscan fossils from the Alcatraz Terrane



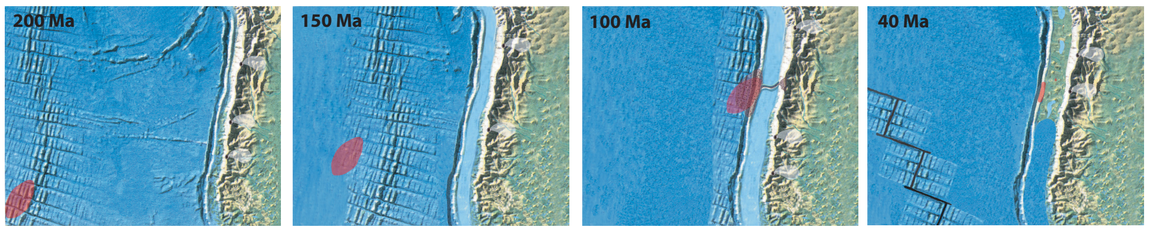
Douvilleiceras mammillatum

Mantelliceras

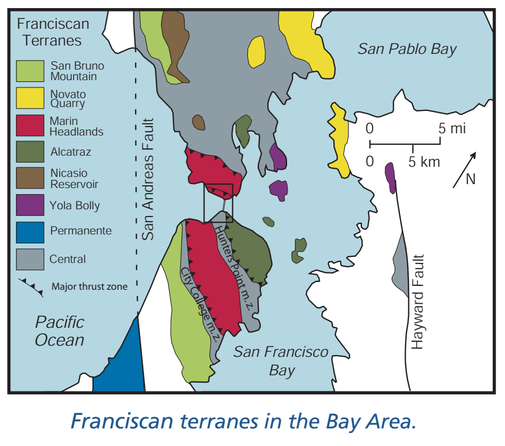
Molluscan fossils from the Marin Headlands Terrane



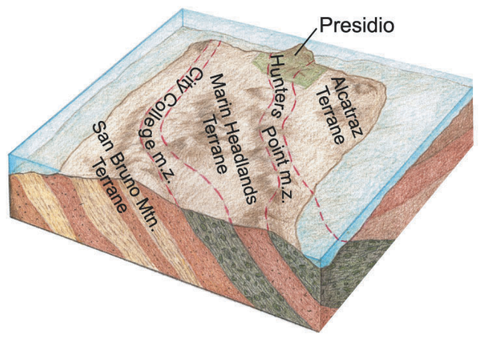
Geologic map of the Marin Headlands showing duplication of rock units by numerous thrust faults.



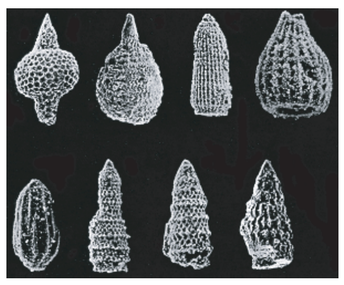
Transport history of the Marin Headlands Terrane (red spot) from the equatorial mid-Pacific to coastal North America.



Franciscan terranes in the Bay Area.



Franciscan rocks underlying San Francisco.



Scanning electron micrographs of silica shells of Radiolaria from the Marin Headlands chert.

Marin Headlands Terrane

The rocks of the Marin Headlands Terrane appear to have traveled long distances since they formed. Tropical fossils and paleomagnetic evidence indicate that the terrane originated near the equator in the central Pacific 200 million years ago. It then moved northeastward with the oceanic plate towards the North American Plate, finally colliding with North America at the latitude of today's Mexico about 100 million years ago. After this oceanic fragment became attached to the North American margin, rather than being subducted under it, faulting produced by northeasterly-directed subduction transported it northward along the western edge of the continent. Finally, San Andreas-related faulting moved it further north along the coast to the Bay Area.